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SHEET 1 OF 1

DOCUMENT CHANGE NOTICE (DCN)

DOCUMENT No. (DOC-REV-GP. ID)	TITLE	NEW REV.
T970151-04-D	ASC Initial Alignment Procedures	C

CHANGE DESCRIPTION (FROM/TO):

REASON FOR CHANGE:

Added 4K alignment procedures and setup data.

ACTION: [X] Incorporate change [ ] Attach DCN to drawing(s) [ ] Other action (specify):

DISPOSITION OF HARDWARE (IDENTIFY SERIAL NUMBERS)	DCN DISTRIBUTION (X=incl. docs)
[X] No hardware affected (record change only)	Barish, Coles, Coyne, Lazzarini, Lindquist, Raab, Sanders, Shoemaker, Stapfer, Tyler, Weiss, Whitcomb, Sciolowicz
[ ] List S/Ns which comply already:	
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SAFETY, COST, SCHEDULE, REQUIREMENTS IMPACT? [X] No [ ] Yes (If yes, enter Change Request number)

APPROVALS:	DATE	OTHER APPROVALS (specify)	DATE
ORIGINATOR: Ken Mason KM	7/7/00		
TASK LEADER: M E Zucker	7/17/00		
GROUP LEADER:			
DCC RELEASE: C Cunliffe	7/24/00		

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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ASC Initial Alignment Procedures

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Distribution of this draft:

Detector Group

This is an internal working note of the LIGO Project..

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1 SCOPE

The purpose of this document is to establish the procedures and specify the equipment required to initially align the core optic and detector subsystem components. The procedures described are used to align the core optics on the 2 km arms at the Hanford. WA site and the 4 km arms at both the Hanford and Livingston, LA sites.

Offset centerlines will first be established parallel to the X and Y arms of the interferometer at the corner, mid, and end stations. Optical tooling techniques will then be used to translate these offset centerlines parallel to the beam tube centerline.

Establishing offset centerlines offers two main benefits:

1. Beam tubes can be installed and pumped down prior to the rest of the system being installed and aligned.
2. Future alignment or alignment verification can be done with the beam tubes closed off.

Alignment of each core optic consists of 3 adjustments. They are:

1. Transverse and vertical positioning which will be accomplished by moving the LOS until a set of fiducials are sighted with a theodolite.

2. Axial positioning (along the beamline) which utilizes the electronic distance measurement feature on the theodolite.

3. Angular alignment in which the optic will be oriented by autocollimation.

2 REQUIREMENTS

Initial alignment must set the Nd Yag laser beam within the range of adjustment of the COS such that a transition to acquisition alignment can take place. The specifications required for this to occur is specified in LIGO - T970060-00-D (1):

Angular positioning	+/- 0.1 mrad (ITM, ETM,BS, RM, FM)
Transverse positioning	+/- 1 mm (ITM, ETM)
	+/- 5 mm (BS, RM, FM)
Axial positioning	+/- 3 mm (ITM, ETM,BS, RM, FM)

The angular alignment phase is most critical due to the long length of the arms, as well as the relatively small range of adjustment of the suspended optics (0.8mrad pk/pk). Our goal for angular alignment is 10% of the adjustment range of the suspended optic or .08 mrad. Over a 4 km arm length, a .08 mrad angle will bring us within 320mm to the center of our ETM (See fig. 1).

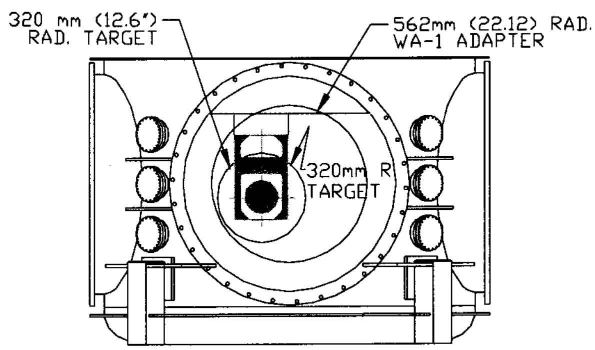


FIG 1. VIEW DOWN END STATION

The Monuments placed as of this date has been found to be within +/- 3mm by Roger's surveying (2). Over a 200 meter separation this results in an error of up to .03 mrad. The total error accumulation including monument locations, procedural and equipment errors is within our goal of .08 mrad as shown in Table 1.

Table 1: Total Error Accumulation

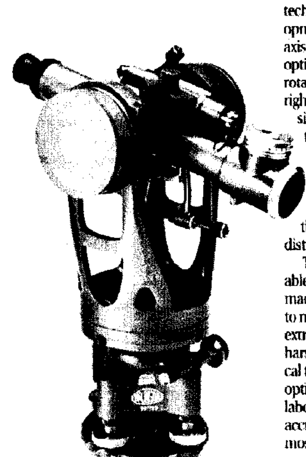
Positioning of monuments	.03 mrad (6 arc seconds)
Sighting of plunb markers	.02mrad (4 arc second)
90 degree autocollimation	.01 mrad (2 arc seconds)
90 degree rotation	.01 mrad (2 arc seconds)
Autocollimation of optic	.01 mrad (2 arc second)
Total	*.08 mrad (16 arc seconds)*

3 EQUIPMENT REQUIRED

The following equipment or their equivalent will be required:

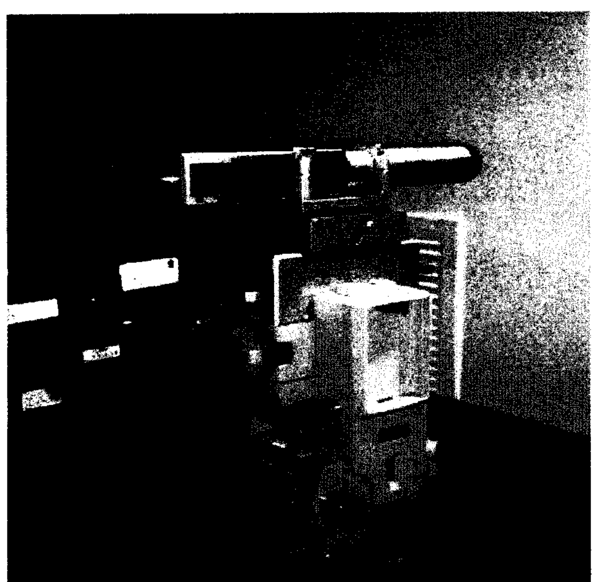
1. One (1) Sokkia Total Station Theodolite model SET2B with electronic distance measurement (EDM), autocollimating eyepiece, tripod, prism, and optical plummet (pictured below with Newport laser autocollimator).
2. One (1) Brunson model 75-H Optical Transit Squares with autocollimating eyepiece, stand, and coincidence level (pictured below).
3. One (1) Newport laser autocollimator Model LDS1000 with mounts to theodolite.
4. Two (2) 101mm dia. optical flats with mounts (Newport #4024OBD.1 & SL101.6).
5. One (1) 4.0"dia pyrex flat, 1/20 wave, double surface parallel to 1 sec, Al Si O coating both sides. Davidson #D617-4P1P
6. One (1) 12.0" PLX Lateral Transfer Hollow Retroreflector # L-20-1-15.75E
7. One (1) 12.0" PLX Lateral Transfer Hollow Periscope # P-20-1-15.75E
8. One (1) 200mm dia optical flat and mount Davidson #D617-8P2S,Al Si 0 1 side.
9. One (1) 200 ft steel tape and tension scale BMI 2473W200T.
10. One (1) Brunson Instrument stand #230-HC and one (1) model 810 stand.
11. One alignment fixture #D980001-A-D with EDM prism and scale.
12. Support stand to bridge conduit & piping LIGO dwgs. D980431 thru D980434.

75-H Optical Transit Square



One of Brunson Instrument Company's technological breakthroughs was the development of the see-thru hollow horizontal axis on the model 75-H. A partially coated, optically flat mirror is mounted inside and rotates with the hollow axis. This provides a right angle check of the telescope's line of sight relative to the horizontal axis. Additionally, the hollow axis allows you to view the mirror from either side of the instrument to turn optical right angles. The hollow axis gives you the power to use several instruments on the same optical reference line without disturbing their positions.

The model 75-H possesses the remarkable ability to "prove" each shot as it is made, removing any possibility of error due to maladjustment from rough handling, extreme temperature changes and other harsh environmental conditions. Now optical technicians no longer need to rely on the optical bench of some distant calibration laboratory. They can verify the instrument's accuracy themselves where it counts the most — ON THE JOB.



4 CALCULATED OPTIC AND THEODOLITE POSITIONS

Offset centerlines with a clear line of sight are located parallel to the beam tube centerlines in the corner, mid and end stations (see fig 3). These are defined as IAM monuments on drawings D970210 shts 1-5 for Hanford (4) and D980499 shts 1-5 (5) for Livingston. The positional accuracy of the initial alignment monuments must be within +/- 3mm of true position in Ligo Global Coordinates. This applies to X and Y position only.

The Z position is determined from actual positions of door flange centerlines. Scribes are located at each Ham and BSC door locations. The positions of these scribes are measured relative to a control point. For Hanford this control point was 1.0572 meters above BTVE1. The amount of translation required (Z_{offset}) is the difference between the calculated design values and the actual locations of the scribes. A scale is placed on the door flange such that the theodolite can measure directly the Z height. Table 2 contains scribe positions in local coordinates for the Hanford corner station as measured by Rogers Surveying.

Table 2: Elevation Scribe Positions

MONUMENT	*ELEVATION*	Z_{actual} *(M)*	Z_{design} *(M)*	$Z_{(offset)}$ *(M)*
WGV-6	100.0000 M	.0033	0.0	.0033
WGV-8	99.9719	-.0248	-.0282	.0034
WHAM1	99.9128	-.0839	-.0870	.0031
WHAM-2	99.9028	-.0939	-.0955	.0015
WHAM-4	99.9014	-.0953	-.0994	.0041
WHAM-6	99.9004	-.0963	-.0993	.0030
WHAM-7	99.8823	-.1144	-.1177	.0033
WHAM-9	99.8931	-.1036	-.1076	.0040
WHAM-10	99.8933	-.1034	-.1054	.0020
WHAM-12	99.8952	-.1015	-.1055	.0040
WBSC-2	99.9996	.0029	.0006	.0023
WBSC-4	99.9937	-.0030	-.0053	.0023
WBSC-7	99.9935	-.0032	-.0052	.0020
WBSC-8	99.9993	.0026	+.0005	.0021
WBSC-8 SW	99.9975	.0008	+.0005	.0003

Table 2: Elevation Scribe Positions

MONUMENT	*ELEVATION*	Z_{actual} *(M)*	Z_{design} *(M)*	$Z_{(offset)}$ *(M)*
LBSC-1	-	-.007	-.001	.006
LBSC-2	-	-.014	-.001	.013
LBSC1-1	-	-.011	-.002	.009
LBSC1-2	-	-.012	-.002	.009
LBSC1-3	-	-.014	-.004	.010
LBSC1-4*	-	-.010	-.004	.006
LBSC3-1*	-	-.013	-.003	.010

* Indicates preferred monument

There are several factors which effect the Z-position and pitch of the optics. The curvature of the earth and physical orientation of the beam tube have to be factored into the setup parameters.

The beam tube orientation and earrth curvature add to give the difference between global and local coordinates. This angle was calculated by Albert Lazzarini in Ligo-T980044 (6)from best fit survey data. The curvature of the earth puts our bubble levels at different angles to the straight line formed by the beam tube. We therefore add this constant angle to our beam tube orientation to properly position the theodolite. This data is summarized in table 3. The total angular compensation is added to the pitch orientation of the theodolite.

Tables 4 and 5 contain *optic* positions per Ligo-T970091 (3) and theodolite/autocollimator positions and orientations. The theodolite/autocollimator data was found by taking the surface normals for each of the optics (T970091) and extending the vector until it intersected the plane created by the offset centerlines (fig 2). This data includes compensations for curvature of the earth and physical orientation of the beam tubes.

The height of the theodolite does not include the offset distance between the theodolite and the autocollimator and the actual Z scribe reference. The theodolite separation can change therefore must be measured and then subtracted from the value given in tables 4 and 5 column 8.

e.g. In setting the Hanford MMT3 optic the measured separation was 153.2 mm and we used the scribe on WBSC-8 SW.

Therefore Z-final = Ztheo - Zg - Zsep

Z-final = -19.135 mm-.30 mm -153.2 mm   Zsep = measured distance

Z-final = -172.6 mm   Ztheo = value in table 5

Zg = value in table 2

Table 3: Global Direction Cosines

	CORNER	*MID STATION*	*END STATION*
X-ARM WA	-619 microrad	-305.83 microrad	7.84 micro-rad
Y-ARM WA	12.5 microrad	325.84 microrad	639.20 microrad
X-ARM LA	-312 microrad	-	314.7 microrad
Y-ARM LA	-611 microrad	-	18.77 microrad

Fig.3. LLO Scribe Locations

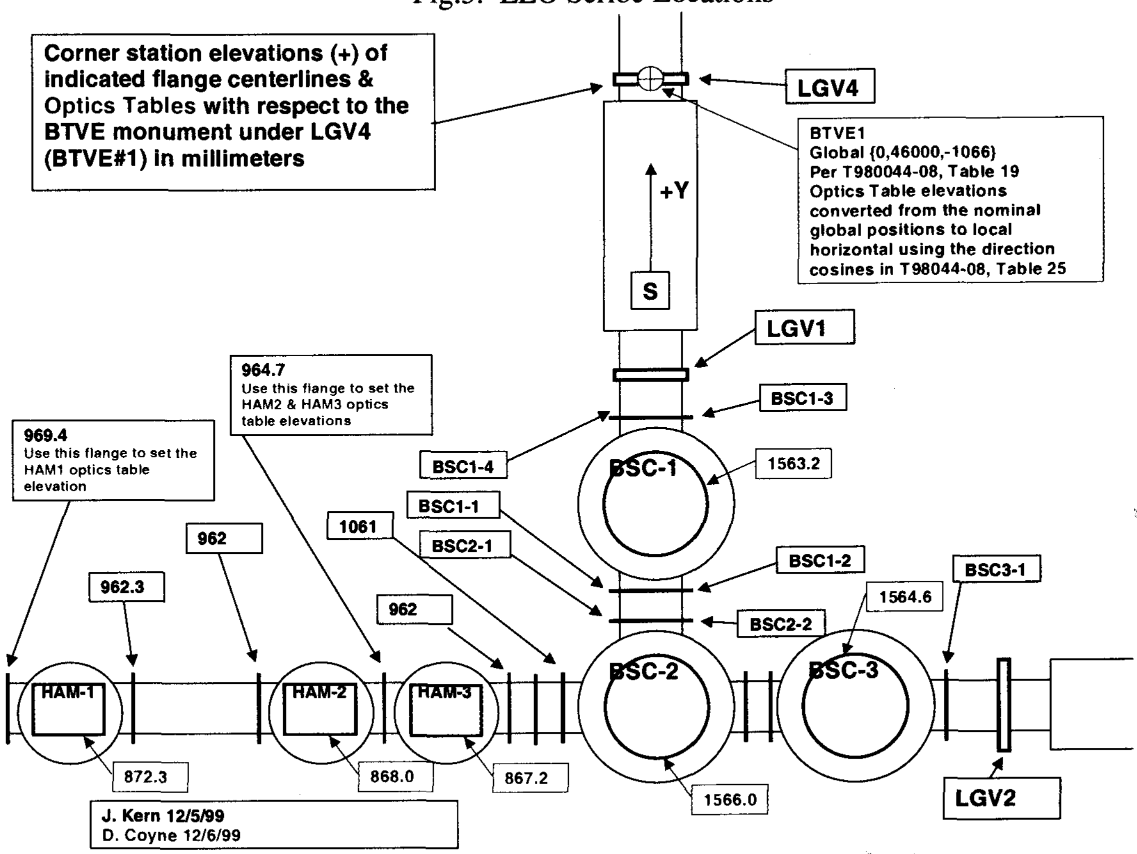


Table 4: OPTIC AND THEODOLITE POSITIONS (2K)

Optic	X optic	Y optic	Z optic	*Monument*	X theodolite	Y theodolite	Z theodolite	Yaw theodolite	Pitch theodolite	Axial distance
LIGO GLOBAL COORDINATES							LOCAL COORDINATES			
MMT3	29510.7	9062.1	43.1	IAM13	-3251.1	9305.2	19.13	90°25'30	89°55'23	32763
RM	12184	9060	43	IAM14	-3251.1	9060	-246.8	89°59'32	88°57'9"	15438
RM(a)	12184	9060	43	IAM14A	-3251.1	8657.8	-246.8	89°59'32	88°57'9"	-
OF_y	1614	9072	-95.0	IAM26	-3251.1	9072.1	-108.0	89°59'4"	89°50'43	-
$OF_{y(a)}$	971.6	9678.8	-96.7	IAM82	-3251.1	7895.3	-96.5	67°29'42	90°0'0"	-
FM_y	199.6	9072.4	-96.3	IAM29A	200.9	38154	-2.4	270°0'7"	90°11'23	29082
$FM_{y(a)}$	199.6	9072.4	-96.3	IAM81A	-3251.1	9707	-84.7	89°59'16	90°9'58"	-
ITM_y	199.6	9569.1	-98.1	IAM29	199.6	38154	-98.5	270°0'0"	90°0'2"	28585
ETM_y	199.6	2018689	-98.1	IAM121	199.6	2012861	-100.0	270°0'0"	89°58'52	5828
OF_{bs}	10184	9060	-13.2	IAM27	-3251.1	8660.7	-103.8	270°0'0	89°38'24	-
$BS_{(2k)}$	9162.6	9059.6	-14.0	IAM32	9163	-3251.2	9.3	270°0'4"	90°9'47	12311
OF_x	9166.2	400	-103.7	IAM32A	9164.4	-3251.2	-121.4	270°1'41	89°48'38	-
FM_x	9162.6	-199.6	-98.4	IAM33A	38154	-186.2	-81.9	89°58'25	90°2'38	28991
ITM_x	9686.6	-199.6	-100.3	IAM33	38154	-199.6	-123.0	0°0'0"	89°57'52	28467
ETM_x	2018807	-199.6	-100.3	IAM131	2012860	-199.6	-98.4	270°0'0"	90°1'5"	5947

(a) designates an alternate method when the line of sight is blocked by an optic or baffle.

Table 5: OPTIC AND THEODOLITE POSITIONS (4K LIVINGSTON))

Optic	X optic	Y optic	Z optic	*Monument*	**X** theodolite	**Y** theodolite	**Z** theodolite	**Yaw** theodolite	**Pitch** theodolite	*Axial* dist.
MMT3	-20883.6	207.8	25.6	IAM78	11600	-8.7	-27.6	90°22'55"	89°53'42"	32484
RM	-4596.0	212.0	26.0	IAM77	11600	214.1	-283.9	89°59'34"	88°53'57"	16199
OF_{bs}	-1740.0	212.4	-27.5	IAM77	11600	214.1	-283.9	89°59'34"	88°53'57"	-
ITM_x	4669.7	199.5	-100.9	IAM76	11600	199.5	-103.1	90°0'0"	89°58'54"	6930
$BS_{(2k)}$	-199.4	212.6	-57.0	IAM90	-199.54	11600	-175.8	89°24'11"	89°59'58"	11388
ITM_y	-199.4	4805.2	-98.1	IAM91	-199.4	11600	-102.3	90°0'0"	89°57'52"	6795
ETM_y	-199.4	3999860	-98.1	-	200.6	4002365	-98.3	270°0'0"	90°0'04"	2505
ETM_x	3999725	199.5	-100.9	-	3993700	199.5	-104.6	90°0'0"	89°58'54"	6025

5 2K ALIGNMENT PROCEDURES

5.1. ALIGNMENT OF MMT3 AND RM

1. Prepare vacuum equipment. Place clean rooms over WHAM 7, WHAM9 and WBSC8. Doors must be removed to allow loading of the LOS and line of sight for alignment equipment (See fig. 5)

2. Place the LOS with the MMT3 optic suspended onto the optics table in Wham7 in its approximate location (see fig 4).

3. Mount the autocollimator to the theodolite. Mount such that the adjustment screws are on the right when looking into the scope. Strain relieve the autocollimator cable to the clamp supplied.

4. Mount the autocollimator/theodolite on the Brunson stand and position over IAM 13. Level the stand with a machinist level and the theodolite with the bubble level. Using the optical plummet, center the theodolite over the monument.

5. Clamp a 300mm or greater scale to the flange protector on WBSC-8, aligning it to the scribe on the side of the flange.

6. Set the 8.0" diameter optical flat between the offset centerline and scale with the top of the mirror just above the $Z_{theodolite}$ position from table 4.

7. The theodolite and autocollimator are next set parallel to one another. To do this first autocollimate the theodolite to the optical flat using the autocollimator kit in place of the eyepiece. When autocollimated to within an arc second, adjust the laser autocollimator orientation with the upper right and lower left adjustment screws on the New Focus mount. Readings can be made by either the digital readout or by an oscilloscope connected to the analog output port on the controller for the laser autocollimator. Each instrument must be autocollimated to within 1 arc sec (5 microradians).

8. Measure the separation between the theodolite scope and the autocollimator scope and record this value. Level the theodolite 180degrees, making sure to encompass the travel the theodolite must move.Calculate the z-heightper page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

9. Rotate towards the monument IAM12 or IAM99 which establishes the offset centerline and align to the monument. Adjust for monument calibration per LIGO-T990017 (7).

10. When aligned to the monument, zero out the horizontal angle and adjust the telescope body to zero the vertical angle. Rotate in yaw and pitch per table 4. The theodolite/autocollimator is now in its final position and should not be moved again.

11. Place the scale on the fixture. With the scale in its upper locked position, the center of the optic should correspond to 6.00" on the scale. Measure off the Z separation (theodolite centerline to autocollimator centerline) on the scale and move the LOS until the theeodolite crosshairs are aligned to this position and the edge of the scale.

12.Remove the scale and replace with the prism. Measure the distance to the prism adding the predetermined offset to the optic face dimension to the measurement. To convert to Ligo Global coordinates subtract the x value of the theodolite (-3251.1mm) from the reading. Adjust the LOS until the correct x position is obtained per table 4.

13. Remove the prism to begin autocollimation of the optic hr surface with the laser autocollimator. Place the autocollimator in analog mode and put 2 oscilloscopes in parallel. One should be placed near the autocollimator and the other placed in sight of the person adjusting the alignment fixture.

14. There will probably be 2 reflections off the optic. Distinguish between the reflection off the HR surface and the AR surface. Locate the reflection off the HR surface and guide the reflection through the tube back toward the autocollimator. Adjust manually until a reading is made within 20 microradians. Fine adjustment can now be made by moving the permanant magnets.

15. Once the optic is in its final position, turn on the laser for the optical lever and steer the beam onto the photodetector until it is nulled out.Calibrate the optical lever per Calibration of Optical Levers, LIGO-T990026 (9).

16. Alignment of the RM is identical to MMT3 using the positions found in table 4 and positioning over IAM-14.

17. The doors are replaced and clean rooms removed.

Fig 4. Optical Table Layout

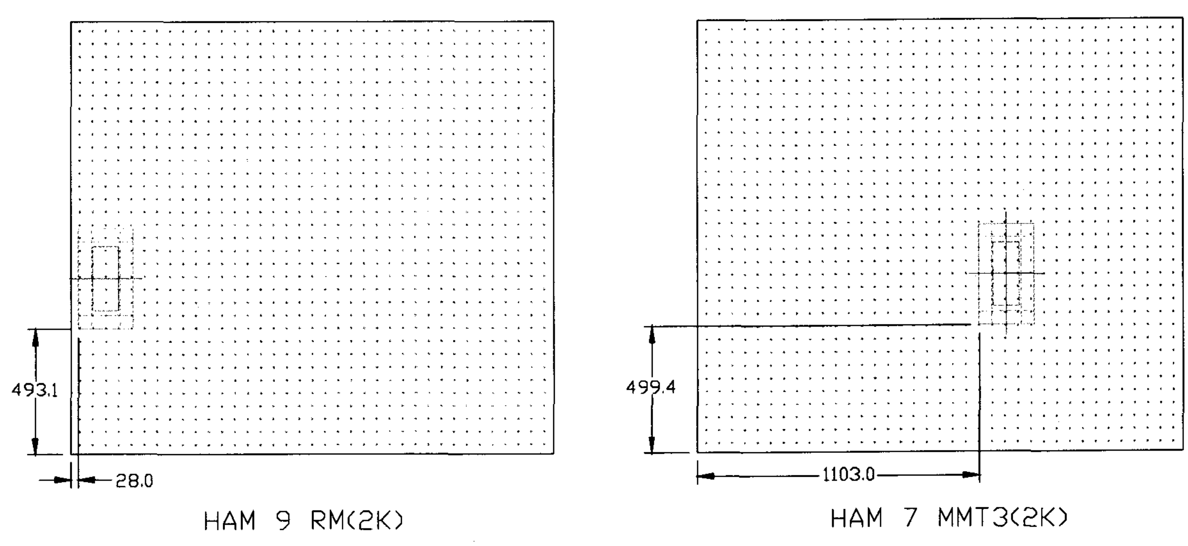
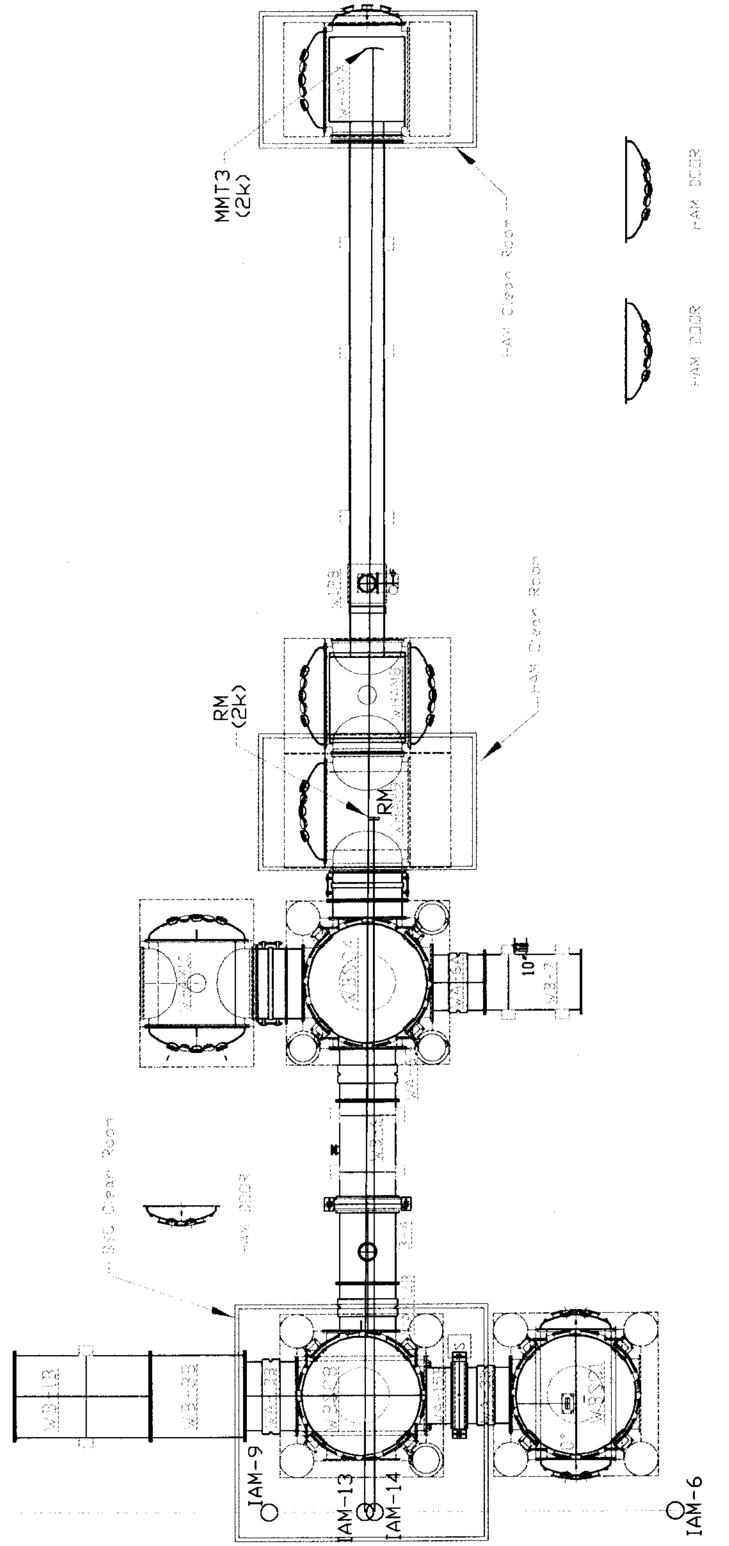


Fig. 5



5.2. ALIGNMENT OF BEAM SPLITTER OPTICAL FLAT

1. Prepare vacuum equipment. Place clean rooms over WBSC-8 and WA-1B. Remove the door on WBSC-8 and adapter WA-1B to allow loading of the LOS and a line of sight for alignment equipment.

2. Place the optical flat and mount into adapter WA-12B in its approximate location as shown in fig.6.

3. Mount the autocollimator to the theodolite. Mount such that the adjustment screws are on the right when looking into the scope. Strain relieve the autocollimator cable to the clamp supplied.

4. Mount the autocollimator/theodolite on the Brunson stand and position over IAM 26. Level the stand with a machinist level and the theodolite with the bubble level and then internal level. Using the optical plummet, center the theodolite over the monument.

5. Clamp a 300mm or greater scale to the flange protector on WBSC-8, aligning it to the scribe on the side of the flange.

6. Measure the separation between the theodolite scope and the autocollimator scope and record this value. Level the theodolite 180 degrees, making sure to encompass the travel the theodolite must move.Calculate the z-height per page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

7. Set the 8.0" diameter optical flat between the offset centerline and scale with the top of the mirror just above the $Z_{theodolite}$ position from table 4.

8. The theodolite and autocollimator are next set parallel to one another. To do this first autocollimate the theodolite to the optical flat using the autocollimator kit in place of the eyepiece. When autocollimated to within an arc second, adjust the laser autocollimator orientation with the upper right and lower left adjustment screws on the New Focus mount. Readings can be made by either the digital readout or by an oscilloscope connected to the analog output port on the controller for the laser autocollimator. Each instrument must be autocollimated to within 1 arc sec (5 microradians).

9. Check the separation between the theodolite scope and the autocollimator scope and record this value. Check that the theodolite is level 180 degrees, making sure to encompass the travel the theodolite must move. Recalculate, if necessary, the z-height per page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

10. Rotate towards the monument IAM12 and IAM99 which establishes the offset centerline and align to the monument. Adjust for monument calibration per LIGO-T990017 (7).

11. Position the optical flat such that the autocollimator beam is approximately centered on the 4.0" dia. optical flat.

12. Adjust the optical flat mount until autocollimated within 1 arc sec (5 microradians).

13. The optical flat is in its final position and must not be moved or bumped.

5.3. ALIGNMENT OF THE BEAMSPLITTER

1. Prepare vacuum equipment. Place clean rooms over WBSC-4 and WBSC-8. Doors must be removed to allow loading of the LOS and line of sight for alignment equipment.

2. Place the LOS with the BS optic suspended into WBSC-4 in its approximate location as shown in fig.8.

3. Mount the autocollimator to the theodolite. Mount such that the adjustment screws are on the right when looking into the scope. Strain relieve the autocollimator cable to the clamp supplied.

4. Mount the autocollimator/theodolite on the Brunson stand and position over IAM 32 plus .7071(A) per fig.6. Level the stand with a machinist level and the theodolite with the bubble level. Using the optical plummet, center the theodolite over the monument.

5. Clamp a 300mm or greater scale to the flange protector on WBSC-7, aligning it to the scribe on the side of the flange.

6. Set the 8.0" diameter optical flat between the offset centerline and scale with the top of the mirror just above the $Z_{theodolite}$ position from table 4.

7. The theodolite and autocollimator are next set parallel to one another. To do this first autocollimate the theodolite to the optical flat using the autocollimator kit in place of the eyepiece. When autocollimated to within an arc second, adjust the laser autocollimator orientation with the upper right and lower left adjustment screws on the New Focus mount. Readings can be made by either the digital readout or by an oscilloscope connected to the analog output port on the controller for the laser autocollimator. Each instrument must be autocollimated to within 1 arc sec (5 microradians).

8. Measure the separation between the theodolite scope and the autocollimator scope and record this value. Level the theodolite 180degrees, making sure to encompass the travel the theodolite must move.Calculate the z-heightper page 8 and set the crosshairs in the theodolite to the appropriate mark on the scale.

9. Rotate towards the monument IAM3 which establishes the offset centerline and align to the monument. Adjust for monument calibration if necessary.

10. When aligned to the monument, zero out the horizontal angle and adjust the telescope body to zero the vertical angle. Rotate in yaw and pitch per table 4. The theodolite/autocollimator is now in its final position for positionining the optic.

11. Place the scale on the fixture. With the scale in its upper locked position, the center of the optic should correspond to 6.00" on the scale. Measure off the Z separation (theodolite centerline to autocollimator centerline) on the scale and move the LOS until the theeodolite crosshairs are aligned to this position vertically.

12.Remove the scale and replace with the prism. Measure the distance to the prism adding the predetermined offset to the optic face dimension to the measurement per fig.6.

13. Place the theodolite/autocollimator over IAM32 and repeat steps 4 thru 10 above. The autocollimator should be in its final position for angular alignment per Table 4. Place the autocollimator in

analog mode and put 2 oscilloscopes in parallel. One should be placed near the autocollimator and the other placed in sight of the person adjusting the alignment fixture.

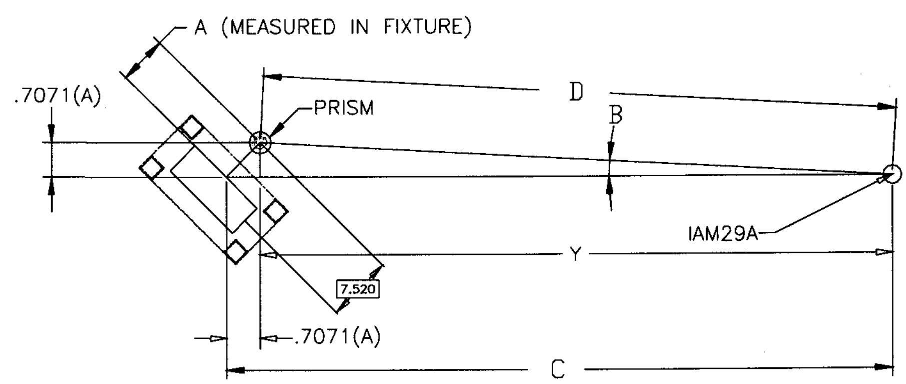
14. There will probably be multiple reflections off the optic. Distinguish between the reflection off the HR surface and the AR surface as it comes off the beamsplitter and hits the optical flat. Locate the reflection off the HR surface and guide the reflection through the tube back toward the autocollimator. Adjust manually until a reading is made within 20 microradians. Fine adjustment can now be made by moving the permanant magnets to within 5-10 microradians.

15. Once the optic is in its final position, turn on the laser for the optical lever and steer the beam onto the photodetector until it is nulled out.Calibrate the optical lever per Calibration of Optical Levers, LIGO-T990026 (9).

16. Remove the optical flat and PLX retroreflector from WBE-3A2.

17. The doors are replaced and clean rooms removed.

FIG. 6



1. MEASURE DISTANCE A.
2. CALCULATE OFFSET = .7071(A).
3. CALCULATE ANGLE B
   TAN B = .7071 (A) / Y
4. SET UP THEODOLITE AND POSITION PRISM IN TRANSVERSE AND VERTICAL POSITION.
5. CALCULATE DISTANCE FROM THEODOLITE TO PRISM
   COS B = Y / D
6. SET AXIAL POSITION D WITH THEODOLITE
7. RECHECK TRANSVERSE POSITION AND MOVE IF NECESSARY